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A COMPARISON OF THE VARIOUS HELICOPTER MATHEMATICAL MODELS USED IN THE METHODOLOGY ASSESSMENT

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Abstract

Various features of the computer codes used in the helicopter industry and by government agencies for rotorcraft aeroelastic stability analysis are compared. Mathematical rigor in modeling rotorcraft is given primarily to the rotor-system dynamic behavior; the aerodynamic modeling is still limited to strip theory and to an uneven application of corrections for stall, reversed flow, yawed flow, radial flow, and unsteady aerodynamic effects. The forward-flight regime analysis is included in five of the 11 codes surveyed. However, only two of these codes are capable of a Floquet analysis for aeroelastic stability. For the hover regime, nine of the 11 codes use eigenanalysis approach. The remaining codes perform a harmonic analysis of the transient response of system.

Nomenclature

The following abbreviations are used in Tables 1-6.

A = articulated rotor

Ae = aerodynamic center

Army-AL = Army Aeromechanics Laboratory

Ax = axial flight

B = bearingless rotor

BHT = Bell Helicopter Textron

BM = need in code for blade mode shapes

BV = Boeing Vertol

C = center of gravity

Cn = cone

CP = capability present for feature indicated

D = droop

E = elastic axis

EDT = engine/drive-train modeled

EXT = external

F = forward flight

FE = finite element

G = gimballed rotor

GDOF = gimbal degree of freedom

H = hingeless rotor

HH = Hughes Helicopter

Ho = hover

INT = internal

N = neutral axis

NA = not available in code

NHOT = no higher-order terms

PRM = pitch-roll motion

RTTrans = rotor trim from transient (20/30 REVS)

S = semiarticulated rotor

SA = Sikorsky Aircraft

SE = simple equation

Sw = sweep

T = teetering rotor

TA = transient analysis

TBA = to be added

TLU = table lookup

UTRC = United Technologies Research Corporation

Introduction

The purpose of this paper is to present comparisons of the analytical tools used by helicopter manufacturers and the government to evaluate the data sets described in the Integrated Technology Rotor (ITR) studies that were reported on in the Methodology Assessment Workshop. Although almost every technical paper describes an analytical approach the results of which are compared with theoretical, experimental, or flight data, there are few papers that try to compare all analytical tools in a particular area. In helicopter-related studies, two prominent surveys come to mind. The first was a survey conducted by Ormiston in 1974 in which he compared analytical loads results for a hypothetical helicopter rotor.[1] The loads predictions were contributed by segments of the manufacturing and government communities. Ormiston's paper revealed major shortcomings in the analyses of that period. The second survey was conducted by Johnson in 1978 (Ref. 2). That survey compared the features of a broad range of major computer codes in areas of performance, loads and vibration, handling qualities, and aeroelastic stability. Although Johnson only tabulated features of the codes and not results, his work influenced the requirements to be set forth in the government's Second Generation Comprehensive Helicopter Analysis System (2GCHAS) Project. It also provided important guidelines for the CAMRAD (Refs. 3-5) computer code which Johnson has since developed.

The comparisons that follow are patterned after Johnson's survey, although with a narrower focus since only aeroelastic stability codes are considered. Further, only those codes used in the ITR investigations are reviewed. The analytical comparisons with the experimental data are the burden of other papers, contained in the Methodology Assessment report, that will be presented here.

Interestingly, some of the codes that were surveyed in Refs. 1 and 2 are still in use today. They have been the subjects of continual development, however, and determining their present capabilities is difficult.

Codes Surveyed

The 11 codes that are reviewed here are listed in Table 1. The organizations that developed the codes, the code identifications used in the assessment study, the flight regimes to which the codes apply, the solution methods used in the codes, and references that contain additional information about the codes are included in the table. The first eight codes in the table were developed by the major helicopter manufacturers; the last three codes were developed by government agencies. The industrial codes, as indicated earlier, have been developed over a relatively long period of time. Three versions of the E927 code are now in use as indicated in the table. The DART code is a more mature and helicopter-oriented version of the SADSAM code, and the CAMRAD code is the most recently developed and comprehensive code used in the assessment study. The last two codes, PFLT and FLAIR, were developed as research tools whose purpose it was to demonstrate modeling refinements in aeroelastic stability analysis; as such, they are applied to idealized rotorcraft models. They are predecessors to a finite-element-based code that is currently under development,[19] but it was not available for the assessment study. The first nine codes are referred to herein as applied codes and the last two as research codes.

In the tables that follow, it was necessary to make extensive use of abbreviations. Those used in a given table are defined in the footnotes to that table. For added convenience, all abbreviations are defined in the nomenclature list at the beginning of the paper.

Past Aeroelastic Stability Codes Survey

As a reference point, a comparison taken from Ref. 2 is shown in Table 2. The table includes only those codes used in the ITR study and not all the codes or features considered in Ref. 2. The code discussed in Ref. 20 is a predecessor to the CAMRAD code.

Table 2 presents a review of the code capabilities in 1978. Basically, the codes concentrated on adequately modeling the rotor and, as a result, were able to treat a variety of hub types; the mathematical models included complete blade motion. The basic disparity seemed to be in the area of the treatment of inflow dynamics. There are also restrictions built into some codes regarding the types of configurations they can analyze. The basic configuration restriction is that only one rotor system can be modeled. A note is in order concerning consistency of the code for trim and blade modes with the codes that actually perform the stability analyses: in some cases, the trim and modal analyses are performed by external programs.

Table 1 Computer codes used in methodology assessment

Code	Developer[a]	Code identification	Flight regime[b]	Solution method	References
DRAV21	BHT	BH	Ho	Eigenvalue	Not available
C81	BHT	BH	Ax,F,Ho	Time-history	6-8
C90	BV	BV	Ax,Ho F	Eigenvalue Floquet	9,10
DART	HH	HH_1	Ax,Ho F	Eigenvalue Time-history	11
E927-1	HH	HH_2	Ax,Ho	Eigenvalue	12
E927-2	SA	SA_2	Ax,Ho	Eigenvalue	12
E927-3	SA	SA_3	Ax,Ho	Eigenvalue	12
G400	SA(UTRC)	SA_1	Ax,F,Ho	Time-history	12-15
CAMRAD	NASA	NA	Ax,Ho F	Eigenvalue Floquet	3-5
PFLT	Army AL	AL	Ho	Eigenvalue	16
FLAIR	Army AL	AL	Ho	Eigenvalue	17,18

[a]Army AL = Army Aeromechanics Laboratory; BHT = Bell Helicopter Textron; BV = Boeing Vertol; HH = Hughes Helicopter; SA = Sikorsky Aircraft; SA(UTRC) = Sikorsky Aircraft (United Technologies Research Corp.).

[b]Ax = axial; F = forward; Ho = hover.

Table 2 Aeroelastic survey from Ref. 2

Feature	E927	G400	C81	Ref. 20
All helicopter configurations	NA	NA	CP	CP
All rotor types	CP	CP	CP	CP
Helicopter trimmed	NA	*a*	CP	CP
Elastic airframe motion	CP	CP	*b*	CP
Complete blade motion	CP	CP	CP	CP
Inflow dynamics	NA	CP	NA	CP
Aerodynamic interference	NA	NA	CP	CP
Programs completely coupled	NA	*c*	*c*	CP

Notes: CP = capability present; NA = not available.

[a]Partial trim.

[b]Shaft or pylon elastic motion only.

[c]Needs blade mode shapes.

Basic Features of Aeroelastic Stability Codes

Table 3 presents the same features for present codes as shown in Table 2 for 1978 codes. As in 1978, there are still only two codes that are capable of modeling more than a single rotor configuration (C81 and CAMRAD). The hub types considered by the various codes are indicated in the table. The applied codes (in the first nine columns) all show excellent capability in modeling a variety of hub conditions. There has been marked improvement in the consistency of the treatment of trim and stability models and the coupling of these models. The treatment of dynamic inflow as degrees of freedom is more of a standard today than it was in 1978. Modeling improvements in the treatment of the airframe have also advanced.

The Mathematical Model

The structural and aerodynamic modeling details for the codes are shown in Tables 4 and 5, respectively. The rotor system configuration limitations are shown in the first row of Table 4. Next, the blade modeling details are shown. Most of the codes use a modal synthesis of the blades. In the table, the solidus (/) indicates when the blade modes are uncoupled. The bending and torsion modes are uncoupled in the E927 versions and the bending flap, and lag and the torsion modes are uncoupled in G400. The number of blade modes required is often small, but the range of modes allowed by the codes is from five to 15. The use of more than five modes may be critical in detailed correlation studies. The modeling refinement in most codes is limited to 20 segments, although the CAMRAD code allows up to 50 segments. Some features that could advantageously be added to some of the codes include modeling of blade droop and sweep, noncoincident hinges, removal of small-angle restrictions on twist angles, and the capability of including fuselage aerodynamic loads. There are two codes, the G400 and CAMRAD, capable of handling rotor speed as a degree of freedom. Another modeling sophistication included by G400, DART, FLAIR, and, possibly, C90 is the ability to model redundant load paths. The codes that obtain the stability characteristics via eigenanalysis all use multiblade coordinates. This statement requires some qualification, however. As shown in Table 1, DART, G400, and C81 determine their stability characteristics via a transient response reduction analysis. The multiblade coordinates in G400 and C81 are actually used in analyses other than aeroelastic stability. All of the applied codes are capable of modeling an elastic fuselage as well as a pylon. In addition, CAMRAD is capable of including an engine/drive-train model.

In Table 5, it is seen that aerodynamic strip theory is used in all codes. It is surprising to find that some of the enhancements, most of which are simple to include, are not common to all the applied codes. Reversed flow, yawed flow, nonuniform inflow, and dynamic inflow are examples of corrections which could easily be included. The preferred treatment of determining aerodynamic coefficients remains a table-lookup procedure, and the treatment of forward flight aerodynamics is included in only five of the codes.

Related Optional Aeroelasticity Algorithms in the Codes

Table 6 summarizes the range of stability analyses available. First, it emphasizes the

Table 3 Present survey of aeroelastic stability codes

Features	DART	DRAV21	E927-2	E927-3	E927-1	G400	C90	C81	CAMRAD	FLAIR	PFLT
All helicopter configurations	NA	NA	NA	NA	NA	NA	NA	CP	CP	NA	NA
Rotor types	ABGHST	ABGHS	ABGHS	ABGHS	AGH	ABGHST	ABHS	ABGHST	AGHST	ABH	H
Helicopter trimmed	RTTrans	C81	CP	CP	CP	CP	C60	CP	CP	CP	CP
Elastic airframe motion	CP	NA	CP	CP	CP	CP	CP	CP	CP	NA	NA
Complete blade motion	CP	CP	CP	CP	NA	CP	CP	CP	CP	NA	NA
Inflow dynamics	CP	CP	CP	CP	CP	CP	NA	NA	CP	NA	NA
Dynamic stall	TA	NA	CP	CP	CP	CP	NA	CP	CP	NA	NA
Nonuniform inflow	CP	CP	CP	CP	NA	F389	NA	CP	CP	NA	NA
Aerodynamic interference	NA	NA	NA	NA	NA	NA	NA	CP	CP	NA	NA
Programs coupled	CP	BM	CP	CP	CP	CP	BM	BM	CP	CP	CP
Free wake geometry	NA	NA	NA	NA	NA	NA	NA	NA	CP	NA	NA

Notes: (1) Rotor types: A = articulated; B = bearingless; CP = capability present; G = gimballed; H = hingeless; NA = not available; S = semiarticulated; T = teetering.

(2) BM = need for blade mode shapes; RTTrans = rotor trim from transient (20/30 REVS); TA = transient analysis.

Table 4 Structural mathematical modeling details

Feature	DART	DRAV21	E927-2	E927-3	E927-1	G400	C90	C81	CAMRAD	FLAIR	PFLT
Rotors	1	1	1	1	1	1	1	2	2	1	1 Blade
Number of blades	2-5	3,4	≥3	≥3	≥3	2-5	Even No.	≥2	≥2	≥3	NA
Blade modes, bending/torsion[a]	FE	10	4/1	4/1	4/1	5-3/2	10	11	10/5	NA	15
Segments	15	20	20	20	20	20	25	20	50	26	1
Offsets	Ae,C,E,N	Ae,C,E,N	Ae,C,E,N	Ae,C,E,N	Ae,C,E,N	Ae,C,E,N	Ae,C,E,N	Ae,C,E,N	Ae,C,E,N	Ae,C,E	NA
Nonuniform mass/ stiffness matrices	CP	CP	CP	CP	CP	CP	CP	CP	CP	NA	NA
Noncoincident hinges	CP	CP	NA	NA	NA	NA	CP	CP	CP	NA	NA
Blade twist angles	CP	Nonlinear	CP	CP	CP	Nonlinear	CP	CP	CP	NA	NA
Blade orientation	Cn,D,Sw	Cn,D	Cn	Cn	Cn	Cn,D,Sw	Cn,D,Sw	Cn,D,Sw	Cn,D,Sw	NA	Cn,D,Sw
Steady-state coupling	CP	NA	NHOT	CP	CP	TA	CP	NA	CP	CP	CP
Rotor speed degrees of freedom	NA	NA	NA	NA	NA	CP	NA	NA	CP	NA	NA
Multi-blade coordination	NA	CP	CP	CP	CP	EDT	NA	CP	CP	CP	NA
Redundant bad paths	CP	NA	NA	NA	NA	CP	TBA	NA	NA	CP	NA
Fuselage	FE/HM	FE	Modal	Modal	Modal	Modal	Modal	Modal	Modal	Modal	NA
Fuselage modes, rigid body/ elastic	6/un/1m	NA	10	10	10	6/10	6/9	6/10	6/10	4/0	NA
Aerodynamics on fuselage	NA	NA	NA	NA	NA	CP	CP	CP	CP	NA	NA
Pylon	CP	PRM	GDOF	GDOF	GDOF	CP	CP	CP	EDT	NA	NA

Notes: Ae = aerodynamic center; C = center of gravity; Cn = cone; CP = capability present; D = droop; E = elastic axis; EDT = engine/drive-train modeled; FE = finite element; GDOF = gimbal degree of freedom; HM = hub modal properties; N = neutral axis; NA = not available; NHOT = no higher-order terms; PRM = pitch-roll motion; Sw = sweep; TA = transient analysis; TBA = to be added.

[a]The solidus (/) designates uncoupled.

Table 5 Aerodynamic modeling features for the codes

Feature	DART	DRAV21	E927-2	E927-3	E927-1	G400	C90	C81	CAMRAD	FLAIR	PFLT
Strip theory	CP	CP	CP	CP	CP	CP	CP	CP	CP	CP	CP
Nonuniform inflow	CP	CP	CP	CP	NA	CP	NA	CP	CP	NA	NA
Dynamic inflow	NA	CP	NA	NA	NA	CP	NA	NA	CP	NA	NA
Radial flow	TA	NA	NA	NA	NA	CP	NA	CP	CP	NA	NA
Solution method	TLU	TLU/SE	TLU	TLU	TLU	TLU/SE	TLU	TLU	TLU/SE	SE	SE
Reversed flow	NA	NA	NA	NA	NA	CP	CP	CP	CP	NA	NA
Stall	TA	CP	CP	CP	CP	CP	CP	CP	CP	NA	NA
Compressibility	TA	CP	CP	CP	CP	CP	CP	CP	CP	NA	NA
Yawed flow	NA	NA	NA	NA	NA	CP	NA	CP	CP	NA	NA
Tip correction	CP	NA	CP	CP	CP	CP	CP	CP	CP	NA	NA
Unsteady aerodynamics	CP	NA	CP	CP	CP	CP	NA	CP	CP	NA	NA
Flight regime	Ax,F,Ho	Ho	Ax,Ho	Ax,Ho	Ax,Ho	Ax,F,Ho	Ax,F,Ho	Ax,F,Ho	Ax,F,Ho	Ho	Ho

Notes: Ax = axial; CP = capability present; F = forward; Ho = hover; NA = not available; SE = simple equation; TA = transient analysis; TLU = table lookup.

Table 6 Related optional aeroelastic stability algorithms in the codes

Feature	DART	DRAV21	E927-2	E927-3	E927-1	G400	C90	C81	CAMRAD	FLAIR	PFLT
Trim	RTTrans	C81	INT	INT	INT	INT	C60	INT	INT	INT	INT
Blade modes	NA	DYNAMO6	INT/EXT	INT/EXT	INT/EXT	INT	Y-71	DYNAMO6	INT	INT	INT
Air resonance	CP	CP	CP	CP	CP	CP	CP	CP	CP	CP	NA
Ground resonance	CP	CP	CP	CP	CP	CP	CP	CP	CP	CP	NA
Time-history	CP	NA	NA	NA	NA	CP	NA	CP	NA	NA	NA
Eigenanalysis	CP	CP	CP	CP	CP	NA	CP	NA	CP	CP	CP
Floquet	NA	NA	NA	NA	NA	NA	CP	NA	CP	NA	NA
Prony's method	NA	NA	NA	NA	NA	NA	NA	CP	NA	NA	NA
Moving block	CP	NA	NA	NA	NA	CP	NA	CP	NA	NA	NA
Harmonic analysis of time-history	CP	NA	NA	NA	NA	CP	NA	CP	NA	NA	NA
Gust response	NA	NA	NA	NA	NA	CP	NA	CP	CP	NA	NA

Notes: CP = capability present; EXT = external; INT = internal; NA = not available; RTTrans = rotor trim from transient (20/30 REVS).

importance of establishing a consistent trim state from which to perturb. It shows that all codes are capable of obtaining flutter (air resonance) and ground resonance solutions. Some codes, such as DART, G400, and C81, approach the aerostability solution via a transient response and have harmonic analysis, moving block, and Prony methods for obtaining the stability solutions from these time-history analyses. Basically, the preferred approach is to rely on eigenvalue and Floquet techniques to obtain the stability data. Only C90 and CAMRAD are capable of performing the Floquet analysis, that is, the direct treatment of periodic coefficients.

Concluding Remarks

The adequacy of these aeroelastic stability codes for application to the ITR data sets will be addressed in subsequent papers to be presented at this forum. The formulation of the codes has been addressed in this paper.

The code formulations are influenced strongly by the highly interdisciplinary nature and complexity of rotorcraft dynamics and aerodynamics. This has caused code developers to make careful approximations of how much of the problem it is prudent to represent. Therefore, in most of the code architectures, the model is built into the code, leaving the analyst with limited options with which to describe the complete rotorcraft configurations in detail. Further, the codes tend to have a rather long life cycle. The disadvantage of this long development is that the older code architectures restrict unnecessarily the dimension space and, therefore, the modeling detail that can be considered. This can be seen in the number of modes and segments allowed. A further problem with the long development period is that the documentation for the codes is often far behind the code capability. These disadvantages are offset, somewhat, by a long period of validation for most capabilities in the codes.

A great amount of mathematical rigor has been placed in accurate dynamic modeling of the rotor system. The rest of the aircraft is often represented as an elastic fuselage using a modal approach. The rigor in the aerodynamic representation is somewhat lacking. The basis for the aerodynamic representation is a semiempirical strip theory. In two codes, CAMRAD and G400, an attempt is made to make this theory as consistent as possible by including reversed flow, yawed flow, radial flow, stall, tip corrections, unsteady aerodynamics, nonuniform inflow, and dynamic inflow.

The treatment of the stability algorithms varies with the flight regimes. For hover (and axial) flight all of the codes except C81 and G400 use an eigenanalysis. For forward flight, in which the coefficients are periodic, only five codes attempt to solve the problem. Of these, only CAMRAD and C90 attempt to solve the periodic coefficient equations directly using an eigenanalysis of the Floquet transition matrix. The DART system has an option which averages the coefficients over a period and then determines the eigenvalues of this "constant coefficient" approximation. The codes that can not address the periodic coefficients directly — C81, DART, and G400 — obtain a time-history solution and reduce that transient response to get the stability characteristics.

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